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**ON THE SIMILARITY BETWEEN COMBUSTION IN A DETONATION WAVE**

**AND IN A ROCKET MOTOR**

**- USSR -**

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## FOREWORD

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ON THE SIMILARITY BETWEEN COMBUSTION IN A DETONATION WAVE  
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[Following is a translation of an article by Yu. N. Denisov, Ya. K. Troshin, and K. I. Shchelkin in Izvestiya Akademii Nauk, otделение tekhnicheskikh nauk Energetika i Avtomatika (News of the Academy of Sciences, Department of Technical Sciences, Power Engineering and Automation), No. 6, 1959, Moscow, Novosibirsk, pages 79-89.]

Thermal gas dynamic analysis of an average image of the combustion process in a rocket engine (RE) shows that the deflagration leg of Hugoniot's curve can be considered as a locus of points each of which uniquely corresponds to a definite degree of the reheating condition of combustion in the RE chamber.

The instability of this process is shown in the heat release chamber and the criterion of instability is revealed. The instability of combustion for a definite degree of reheating results in resonant high frequency oscillations of pressure in the chamber. The instability of the combustion front in a detonation wave is characterized by the same criterion where high frequency pulsations are found experimentally. The decisive role of oblique shock waves is established experimentally in the mechanism of high frequency oscillations during pulsating and spin detonations and, in addition, the absence of a planar wave front. It is proposed that the mechanism of pulsations during detonation is similar to the mechanism of oscillations during combustion in RE chambers.

The contemporary RE is a complex unit in which the basic role belongs to the combustion chamber where a gaseous jet stream is obtained from the products of fuel combustion. However, digressing from the construction details, it is possible to consider the RE combustion chamber (Fig. 1a) as a cylindrical pipe at one end of which to cap g is fed fuel and the oxidizer which forms a mixture -- the parent substance (fuel) -- in area 1. After chemical transformation of the original fuel 1 in combustion zone 2, gaseous products 3 are formed, the specific volume of which appreciably exceeds the specific volume of the original fuel. The emission of these gaseous products from the chamber is choked and accelerated by nozzle 1 by means of which is formed the propellant jet stream.

In order to perfect the RE chambers, it is important to know the conditions and the mechanism of fuel combustion in them. Available data testifies concerning the complexity of the detailed physical-chemical process of combustion in the heat release chamber. However, it is possible to consider the more simple average image of the combustion process in the chamber of an RE. With this purpose in mind, the combustion process as well as the entire combustion chamber are analyzed in a one-dimensional coordinate system of which the axis of the chamber is the z-axis.

No matter how large in actuality in size, combustion zone 2 is complicated and subdivided with regard to the physical-chemical structure. It may be represented as a strong burst during the passage of the substance through which from initial state 1 to the terminal state 3 is given off energy  $Q$ . In addition, the initial state of the substance is characterized by the initial parameter: pressure  $p_1$ , density  $\rho_1$ , temperature  $T_1$ , and flow rate  $u_1$  and the terminal parameters: pressure  $p_3$ , density  $\rho_3$ , temperature  $T_3$ , and flow rate  $u_3$ .

Thermal gas dynamic analysis of such a burst is possible by means of Hugoniot's well known equation which is derived from the law of conservation mass, of the quantity of motion and energy

$$\frac{p_2}{p_1} = \frac{x - \frac{p_1}{p_3} + \frac{2G}{p_1 p_3}}{x \frac{p_1}{p_3} - 1} \quad \left( x = \frac{\gamma + 1}{\gamma - 1} \right)$$

where  $\gamma$  is the ratio of thermal capacity  $c_p/c_v$ .

In addition, it is assumed that in zone 1 the initial substance (liquid or even solid) is transformed by evaporation into an ideal gas which passing through burst 2 preserves the thermal capacity constant and neglects all types of losses by friction, heat transfer and so forth.

The physical concept of the various members of Hugoniot's curve, constructed in Figure 2 at coordinates  $p, V$  (where  $V = \frac{1}{\rho}$  -- specific volume), will become clear if one conducts an analysis of the equation of this curve jointly with Michelson's equation obtained directly from the conservation laws of mass and the amount of motion

$$u_1 = - \sqrt{\frac{(p_3/p_1) - 1}{1 - (V_3/V_1)}} p_1/p_1 \quad (2)$$

From this equation, it is apparent that portion IK of Hugoniot's curve does not possess physical significance because it corresponds to the imaginary values of dispersal velocity of the burst, that is, supercharging [skorost podduba] rate of fuel  $u_1$ .

The upper leg of the curve IE is a series of high velocity conditions of burst distribution, that is, it corresponds to a detonation wave with a given power emission  $Q$ . In accordance to Zhug's law, the dilation front velocity of a detonation is relative to a gas moving in a wave and is equal to the speed of sound  $a$  in the detonation products. Therefore, only one point Zh, describing the condition of a gas in a detonation wave with velocity  $D$ , exists for the leg IE.

Points, lying above Zh, are related to a supercompressed detonation wave, observe for example, during the passage of a detonation from a wide tube into a narrow one [3].

Points, lying on curve IZh, correspond to an undercompressed wave, the existence of which by means of ignition in the shock wave is possible with the given power emission [4].

The lower deflagration leg at KM of the curve corresponds to the dilation rarefaction waves which are accompanied by combustion<sup>1</sup>. (<sup>1</sup>Let us note that the dilation of flame in tubes depending on the border conditions is accompanied also by a compression wave in the initial mixture [5,6,2]. The stationary condition of combustion is stabilized by the border condition of the RE chamber with the compression of the constant amplitude  $p_1$  and a drop of  $\Delta p = p_1 - p_3$  without the emergence of a shock wave.) This leg is divided by the tangent BV into sectors of low (KL) and high (LM) deflagrations. Points, lying in sector LM, do not correspond to real combustion conditions in as much as for their realization more energy would be consumed (similar to sector IZh) than would be emitted during the reaction.

Experimental estimates of the velocities of movement of the flame zone in types relative to the particles of the fuel mixture [2] have shown that combustion rates exist which exceed in tenths the normal combustion rates and result in a conclusion [1 and 2] concerning the physical reality of the entire leg of lower deflagrations (KL). Point L corresponds completely to the evolved deflagration with a burst dilation velocity in the large  $u_1 = u_n$ , when the flow velocity of the reaction's products is equal to the indigenous speed of sound (thermal crisis). Combustion conditions, during which in zone 2, the same quantity of the mixture burns as in the planar front of normal combustion is equal in area to the lateral cross section  $F$  of the chamber and corresponds to the burst dilation velocity  $u_1 = u_n$ .

Michelson's direct fans (see Figure 2) included in the interval  $u_n - u_L$  yield a set of the possible velocities of supercharging  $u_1$ , each of which is possible during the given forcing of the RE chamber operating condition. The higher the velocity of supercharging  $u_1$  and consequently the combustion rate, the greater the drop of pressure  $\Delta p$  along the length of the combustion zone.

Association of the Mach number of supercharging  $M_1 = u_1/a_1$  with the Mach number of escape from the burst  $M_3 = u_3/a_3$  is yielded by the equation obtained from the conservation law of mass

$$M_3 = M_1 \sqrt{\frac{\rho_1 a_1}{\rho_3 a_3}} \quad (3)$$

If forcing of the combustion process in the RE chamber is conducted with a variation of the degree of choking of the escape of gas into the atmosphere from area 3 by means of a different profile of the sub-sonic portion of a Laval nozzle (1), then the relationship of the nozzle taper  $F/F^*$  to the number  $M_3$  has the form

$$\frac{F}{F^*} = \frac{1}{M_3} \left[ \frac{2 + (\gamma - 1) M_3^2}{\gamma + 1} \right]^{\frac{\gamma + 1}{2(\gamma - 1)}} \quad (4)$$

The relation between burst distribution velocity (or the super-charging velocity) and the value of the nozzle taper for constant heat emission  $Q$ , constant chamber cross section  $F$ , and for constant gas parameters in area 1 -  $P_1$ ,  $\rho_1$ ,  $T_1$  -- is illustrated clearly by the two latter equations.

The points of the deflagration leg KL describe the state of reaction products which respond to combustion conditions of the entire set of combustion chambers, each of which is distinguished from the other only by the magnitude of the critical cross section  $F^*$  at the output nozzle.

The lower a point is located on curve KL, the greater deflagration is increased and the less taper is required for bringing up the exhaust velocities of reaction products to sonic velocity in the critical nozzle cross section. For a fully evolved deflagration ( $M_3 = 1$ ), the taper is excessive and then a semi-thermal nozzle is achieved with limited forced combustion conditions.

Thus a consideration of the deflagration leg of Hugoniot's curve as the locus of points, each of which uniquely corresponds to a definite degree of combustion forcing condition in the RE chamber permits, not being devoted alone to the specific mechanism of combustion, conducting an approximate comparative evaluation of the basic engine parameters and of the degree of combustion forcing conditions in the chambers.

If one investigates specifically the combustion mechanism, then a series of indirect considerations concerning the possibility of heating the fuel mixture at the expense of intermixing it with reaction products (liquid RE's) and also at the expense of adiabatic compression (ramjet engines with  $M > 3$ ) give bases to consider that during combustion in heat release chambers of high pressure, a mechanism a gradual self-ignition prevails. (It is understood that this does not exclude the simultaneous existence there of mechanisms of frontal turbulent and micro-diffusion combustion.)

The expressed considerations permit assuming that there is certain similarity between combustion in RE heat release chambers and in a detonation wave. This similarity consists of the following.

First, both in the high pressure chamber and in the detonation wave the prevalence of one and the same combustion mechanism is assumed -- gradual self-ignition with a compressed heat fuel mixture.

Secondly, the average state of the chemical reaction products of both processes is described by thermal gas dynamic equations of the same type and the state of the detonation combustion products is close with regard to pressure (tenths of an atmosphere) and temperature ( $\sim 3000^\circ \text{K}$ ) to the state of combustion products in area 3 of the RE heat release chamber.

Third, the thermodynamically possible fixed combustion conditions for both processes are determined by the intake rate of the fuel mixture into the combustion zone and by the possibility of the mixture's combustion at this rate.

Whereupon the conditional combustion rates of the fuel mixture in the RE chamber ( $u_0$ ) and in the detonation wave ( $D$ ), reduced to the same initial conditions ( $p_0, \rho_0$ ), satisfy the equation  $D/u_0 = \psi$ , where  $\psi$  is the coefficient depending on the pressure in the RE chamber and the degree of combustion chambers,  $\psi$  is found to be close to one.

Besides this, during detonation as well as during combustion in the heat release chamber, deviations of parameters of the gaseous products of the chemical reaction  $p_3, \rho_3, T_3$  and  $u_3$  from the mean value are experimentally observed [7 - 12]. High frequency oscillations, which testify concerning the instability of the combustion zone, are peculiar to both observed processes.

Taking into account the excessive difficulty of experimental and theoretical investigation of the instability and of the combustion mechanism in heat release chambers, it is useful to perform an analysis [13] of one of these processes -- detonation. The study of a single process is found to be essential for knowledge of the other emanating from the similarity of both.

Analysis of combustion stability in a detonation wave, represented as a planar shock wave complex and ignition zone, shows that the imposition of a small disturbance on the combustion zone will result in an increase of this disturbance. Such a conclusion emerges from a following investigation.

In view of the exponential relationship of the chemical reaction velocity to temperature, it is assumed that the gaseous mixture reacts instantly in accordance to the expiration of the induction period  $\tau$ . The wave form, at coordinates  $p$  and  $z$  depicted in Figure 1b, corresponds to this. The distance  $\lambda$  between the leading impact front A of the wave and from Zh, where the chemical reaction is accomplished instantly, is equal to the product of the induction period  $\tau$  times the gas velocity in the wave relative to its front ( $D - w$ ).

The profile of such a wave is presented in Figure 1c with a view towards the simplification of the considered [system] not in the cylindrical but in a two-dimensional system of coordinates  $y$  and  $z$ . The system of coordinates is moved together with a wave in the



direction of axis  $z$  and is associated with both fronts AA and ZhZh. Then from the right the unburned gas with velocity  $D$  enters the front AA; to the left combustion products with the local speed of sound (thermal crisis) enter from burst ZhZh.

Disturbances, appearing to the left of ZhZh, can not be dispersed through the gaseous side, included between ZhZh and AA, because the local speed of sound, at which these disturbances are dispersed, is equal to the output velocity of the combustion products from ZhZh. Nothing however, disturbs the dispersal to these disturbances along the  $y$ -axis.

In the impact compression area AA -- ZhZh, the local speed of sound is higher than the flow rate of the unreacted gas ( $D > w$ ); and therefore, disturbances, emerging to the right of ZhZh, are dispersed in area AA -- ZhZh along both  $y$  and  $z$ -axes both with the current and against the current of the gas.

In actual conditions the quite feasible small disturbance  $b\ c\ b$  is a small distortion of the front ZhZh arising for example as a consequence of the variation of ignition delay  $\tau$  as has been stated above, can be dispersed without difficulty in directions perpendicular to the axis of the pipe  $z$  and this is indicated by the vertical arrows in Figure 1c. In addition, in zones  $b$ , the unburnt gas, compressed initially to pressure  $p_A$ , will be spread, that is, the emerging burst of pressure will attempt to disintegrate in a direction along the  $y$ -axis, to be equal in pressure with the pressure of the surrounding burnt gas  $p_{Zh}$ . Therefore, inside the zones will be found rarefaction waves, the fronts of which are indicated by the dotted lines. Such a dispersal will result in adiabatic cooling of the unburnt gas in zones  $b$  and to the expansion of the ignition delay period  $\tau$  associated with this.

In the region to the right of zone  $c$ , the unburnt and compressed gas, at pressure  $p_A$ , will be compressed even more inasmuch as during the disintegration the burnt gas in zone  $c$  is found to be already adjusted in the direction of the  $y$ -axis. This adjustment of combustion product violates Zhug's rule; in area  $c$  the wave will become compressed with regard to the unburnt gas at the leading front AA of the detonation wave, the compression wave will be dispersed which will also result in a still greater adiabatic heating of the unburnt gas and in association with this, the shortening of the ignition delay period  $\tau$ . Within limits, the unburnt gas in zones  $b$  can be cooled to the temperature  $T = T_A(p_{Zh}/p_A)^{(\gamma-1)/\gamma}$  and to the right of zone  $c$  the unburnt gas will be heated accordingly.

Temperature variation of the unburnt gas in the disturbance zone  $b\ c\ b$  will result in an increase of this disturbance. The limit of disturbance increase is determined by the ultimate increase and decrease of temperature of the unburnt mixture in a disturbance zone and by the corresponding variation of the induction period  $\tau$ . Taking into account the exponential relationship of the ignition



delay period to temperature, one should make the conclusion that the disturbance will increase extra strongly -- structural heterogeneity of the detonation wave will arise.

There is significance in considering only the heterogeneities, which are equal in size with breadth  $\lambda$  of the complex AA - ZhZh, since it is possible to ignore in comparison with  $\lambda$  the small-scale heterogeneity but heterogeneities which are significantly larger than  $\lambda$  will already obviously be not heterogeneities but on the whole will be a curvilinear detonation wave. For heterogeneities, which are comparable with  $\lambda$ , the ignition induction period is the natural time scale of the flow processes in the detonation wave.

Hence, it is possible to formulate the instability condition of the detonation zone with regard to disturbances.

If the disturbance at the combustion front will increase the ignition time by a value which is approximately equal or in excess of the induction period  $\tau$ , then the arbitrary initial distortion of the front will increase and the flat front will lose stability.

If the increase of ignition delay will be small in comparison with induction period  $\tau$ , then the front of the detonation is stable. On the basis of such reasoning, the condition of instability is written as

$$\frac{d\tau}{dT} \Delta T \gtrsim \tau \quad (5)$$

where  $\Delta T$  - is the temperature variation of the gas in the disturbance region,  $d\tau/dT$  - is the ignition delay variation corresponding to a variation of temperature.

The dependence of ignition delay on temperature T and the activation energy E of the reaction is written as

$$\tau = k e^{E/RT} \quad (6)$$

where R - is the gaseous constant, k -- is the pre-factor. The criterion of instability of the flat zone of ignition in a detonation wave is obtained using the pre-factor which does not depend on temperature and pressure

$$\frac{E}{RT_A} \left(1 - \frac{T}{T_A}\right) \gtrsim 1 \quad (7)$$

or if one substitutes the temperatures ratio with the pressures ratio

$$\frac{E}{RT_A} \left[1 - \left(\frac{P_{zh}}{P_A}\right)^{\frac{\gamma-1}{\gamma}}\right] \gtrsim 1 \quad (8)$$

Computation of the criterion for many known detonating gaseous mixtures shows that in virtually all cases, instability must take place.

The result of such instability is high frequency oscillations, the indications of which were first experimentally observed in 1926 by Campbell and Woodhead [8] and later by many other scholars who were

investigating the detonation of various gaseous mixtures in pipes. Photographing the process on a film plate of a detonation wave's dilation which moves in a direction perpendicular to the axis of the tube, they obtain by such means the evolution of this process with time. Photorecords of the detonation of certain gaseous mixtures have an undulatory line of frontal movement and the luminescent band structure of the combustion products (Figure 3) which attest concerning the dispersal of a zone of greater luminescence for the spiral method<sup>1</sup>. (<sup>1</sup>In the photo-scannings of detonations of Figures 3, 4, and 5 the z-axis is disposed horizontally and the time axis t is disposed vertically.) In connection with this, such a detonation process was called the detonation spin in contrast to the observed detonation with a straight line of frontal movement in the photo-scanning and with an absence of an after-glow band structure (Figure 4) in the remaining mixtures and explosive substances.

Further experimental and theoretical investigations [7, 14, 15, and 16] showed that during a spin detonation there occurs a breaking off of the leading front of a detonation wave which occupies a portion of the lateral cross section of the tube and is the supercompressed transverse detonation wave. It was discovered [17] that a spin detonation is always observed in all detonating mixtures which are near the limit of their detonation capacity.

For some time past [12], by application of photo means of greater resolving power, it was possible to establish that photorecords of not only a spin detonation but also of the so-called "normal" detonation wave had a complex structure, the structure of which is schematically presented in Figure 1b. One of such photorecords, obtained by a camera with increased resolving power, is shown in Figure 5 and attests concerning the periodic heterogeneities at a detonation wave front. For study of the nature and mechanism of these heterogeneities, a quite simple method was found to be especially effective which consisted of this -- that a detonation wave is passed through a sufficiently durable, that is, it remains intact after the explosion, glass tube which is covered on the inside with a thin layer of carbon black. On the smoky surface are traces left by the heterogeneities at the detonation front -- that is, by the oblique shock waves are visible. The spacing and number of discontinuities near the tube's surface are computed from the traces.

Analysis of the experimental data of such a "trace" method and of the increased resolving power photo-scanning permitted making inference concerning the existence of two types of detonation waves: spin and pulsating [detonation waves] the trace impressions of which are respectively presented in Figures 7a, 7b, and 6, and 7c. A detonation process with one oblique detonation wave, occupying only portion of the wave front area of the tube's cross section, is related to the spin detonation (Figure 3, 7a, and 7b). In a coordinate system, which moves jointly with the wave front rotationally and progressively, the frontal form remains constant.

An oblique wave, as is clearly visible from Figure 7a, and 7b, possesses in itself a thin structure which gives evidence concerning the periodic heterogeneities in it of the oblique discontinuity type, that is, concerning the instability of the flat structure of ignition and concerning the pulsations for the conditions of this supercompressed oblique detonation wave.

During a pulsating detonation (Figure 5, 6, and 7c) in a coordinate system which moves progressively together with the wave front, the frontal form is changed periodically: the convexities in it alternate with the concavities and vice-versa. Such a variation of the frontal form during a pulsating detonation is a consequence of the periodic collisions of oblique shock waves and of pressure pulsations associated with this at the collision point.

The structural breaking up of a detonation wave with an increase of the mixture's initial pressure is accompanied with an increase of the detonation dispersion rate  $D$  (Figure 8a). Such a variation of the rate  $D$  corresponds to an increase of the theoretically computed mean temperature  $T_A$  in the wave, which results in a decrease of ignition time  $\tau$  and consequently of the ignition zone width [where]  $\lambda = \tau(D - W)$  (see Figures 1b and 8a). In proportion to the decrease of the ignition zone width  $\lambda$  ratio to the tube diameter  $d$ , owing to an increase of temperature  $T_A$  because of an increase of the initial pressure  $p_0$  of the fuel mixture, various conditions are realized from the spin to pulsating detonation with [still] greater values of the number of pulsations  $n$  (Figure 8b) and their frequency  $\nu$ . In Figure 8c, a graph is presented of such a relationship of pulsation frequency  $\nu$  at a detonation front and the number of pulsations  $n$  around the periphery of the tube to the initial pressure of the hydrogen-oxygen stoichiometric mixture for a constant tube diameter.

Thus, it has been experimentally confirmed that the instability of a complex with a flat ignition front will result in a localization of a chemical reaction at individual sectors of the leading front AA of a detonation wave: that is, in the oblique shock waves and the collision points of these oblique discontinuities, where the temperature and density are higher than in a flat wave. In addition to this, in any of the tube cross sections, taken at the inside of zone A - Zh of the schematized detonation complex (see Figure 1b) both the unburnt gas will be included as well as the ignition products.

Regardless of this, however, beyond the real detonation wave, it is possible to develop a control plane Zh - Zh beyond which takes place chemical equilibrium -- the tube is filled either with only combustion products and hence does not have the capacity for the unburnt gas or with combustion products and the unburnt substance which is in a constant proportion.

In an actual RE combustion chamber, the combustion process is also not heterogeneous, whereupon, as has already been noted, there is a basis to assume that the prevailing mechanism of combustion is

the sequential self-ignition of the heated and mixed fuel components. In such a case, the reaction time (the ignition delay period) will be determined by the same expression as for the detonation wave  $\tau = \tau_0 e^{E/RT}$ .

The boundary of combustion zone 2 with area 3 plays the role of control plane Zh - Zh but the role of zone AA - ZhZh is area 2. Consequently, the initial data for the derivation of the combustion instability criterion in an RE chamber is similar to the initial data for the development of the combustion instability criterion during a detonation, and therefore, it is possible to expand all considerations and conclusions concerning the instability of a flat ignition front, made for a detonation, for a heat release chamber.

The combustion instability criterion in an RE chamber is written as

$$\frac{E}{RT_1} \left[ 1 - \left( \frac{p_1 - \Delta p}{p_1} \right)^{\frac{\gamma-1}{\gamma}} \right] \geq 1 \quad (9)$$

where  $\Delta p$  - is the pressure loss throughout the length of the chamber as a consequence of combustion (Figure 2).

For RE chambers, always  $u_1 \ll a_1$  and consequently,  $\Delta p$  is small in comparison with  $p_1$ . Expanding the expression  $[(p_1 - \Delta p)/p_1]^{\frac{\gamma-1}{\gamma}}$  in series according to powers of  $\Delta p/p_1$ , it is possible to ignore the terms, beginning with the second order and then the combustion instability criterion in an RE chamber will take on the form

$$\frac{\gamma-1}{\gamma} \cdot \frac{E}{RT_1} \cdot \frac{\Delta p}{p_1} \geq 1 \quad (10)$$

Proceeding from Michelson's equations directly (2), of Hugoniot's curve (1) and once more ignoring the square of the value  $\Delta p_1/p_1$  with the product  $\Delta p_1/p_1 M_1^2$ , we will obtain  $\Delta p_1/p_1 = 2(\gamma-1) M_1^2 (Q/a_1^2)$ . Now, it is possible to write criterion (10) as

$$(\gamma-1)^2 \frac{E M_1^2}{RT_1} \frac{Q}{a_1^2} \geq 1 \quad (10a)$$

For sufficiently large [values] of  $\gamma$ ,  $E$ ,  $\Delta p$ ,  $M_1$  and  $Q$  and for sufficiently small values of  $T_1$  and  $p_1$ , the left-hand terms of equations (10) and (10a) can achieve a value of approximately one. Then the combustion front stability will be violated and in the chamber pulsations of the combustion front will arise. Because of a negligibly small disturbance drift in the RE chamber ( $w \ll a_2$ ), the size of each pulsation in a direction perpendicular to the  $z$ -axis of the chamber will be approximately two widths of combustion zone 2 and therefore, in the RE chamber cross sectional area it will be set up as of the flame front's pulsations.

$$\gamma_1' = \left( \frac{c}{2\pi} \right)^2 = \left( \frac{d}{2\pi w} \right)^2 \quad (11)$$

The growth time of each disturbance is equal to

$$\tau_g = \frac{\lambda}{a_2} = \frac{2w}{a_2}$$

Reestablishment of the disturbed front proceeds at the filling rate for unburnt gas in area 2. Then the disturbance liquidation time is equal to the ignition induction period  $\tau$

$$\tau_d \approx \frac{\lambda}{a_2} - \frac{2w}{a_2} = \tau$$

The entire period of a pulsation is accumulated from the growth time of a disturbance and of a reestablishment time of the disturbed front. However, for pulsations in a chamber, where  $w \ll a_2$  one can neglect the disturbance growth time of  $\tau_p = \tau w/a_2$  in comparison with  $\tau$  and then the oscillatory process period in the chamber is determined only by the time  $\tau_T = \tau$ . From (11) it is apparent that for width  $\lambda$  of area 2, which is equal to half the diameter of the chamber, the number  $n' = 1$ . In addition to this, oscillations with the fundamental tone frequency  $\nu_0 = 1/2$ , will take place.

When the number  $n' = 2, 3, 4, \dots$ , that is, when the width of area 2 is visibly less than one-half the diameter of the chamber, then there will occur oscillations with the frequency

$$\nu_n = \nu_0 n' = \frac{1}{2} \left( \frac{d}{2\lambda} \right)^2 \quad (12)$$

If the oscillation frequency during a definite stage of combustion forcing in an RE chamber falls in resonance with the intrinsic oscillation frequency of the gas in the chamber, then a large increase of their amplitude is possible.

The resonance mechanism consists of this -- pressure waves with an intensity of the order of  $\Delta p$ , passing through the combustion zone, speed up combustion and they themselves add to the combustion power and increase its amplitude at the expense of this. An approximate estimate shows that the pressure in a compression wave during resonance can achieve double the value of the initial pressure  $p_1$  in the chamber.

Moreover, by the thermal gas dynamic computation [1], it is established that an increase of the combustion rate regarding the particles of a substance will result in a significant increase of pressure in the RE chamber because of the emergence of shock waves. Thus, for an increase of the combustion rate by a multiple of two in the chamber, a compression wave with a pressure four times greater than  $p_1$  arises.

High frequency oscillations during combustion in heat release chambers and during detonation have still been only little studied experimentally and theoretically, however, the above stated similarity of both processes permits us to express the supposition that pulsations in these processes have a similar nature and mechanism.

If in the combustion chamber, a mechanism of frontal turbulent combustion prevails, then the criterion of instability (9) is inapplicable. However, in this case, the thermo-dynamic similarity of combustion in such a chamber with combustion in a detonation wave is preserved.

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# FIGURES

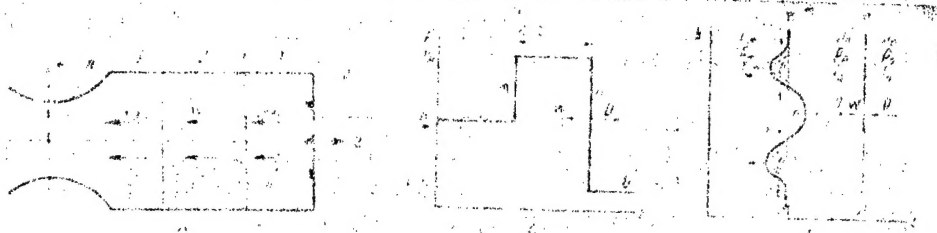


Figure 1. a) diagram of an RE combustion chamber. b) pressure diagram in a schematized flat detonation wave. c) schematic representation of a disturbance in the ignition zone.

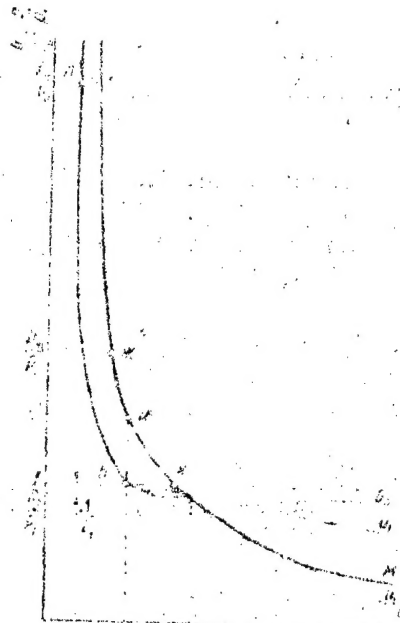


Figure 2. Hugoniot's adiabatic curve. For clarity, both legs of the adiabatic curve EI and KM are drawn for the same effective power-output  $Q$ , not depending on the initial pressure of the reacting mixture.

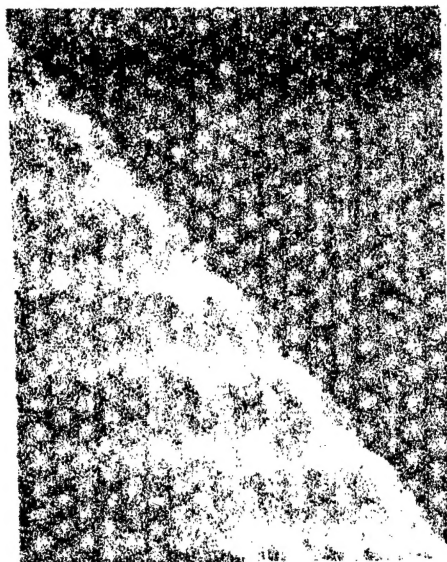


Figure 3. Photorecord of a spin detonation.

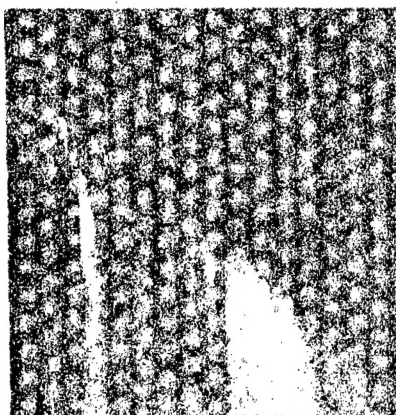


Figure 4. Photorecord of a so-called "normal" detonation. The picture was taken by a camera with low resolving power.

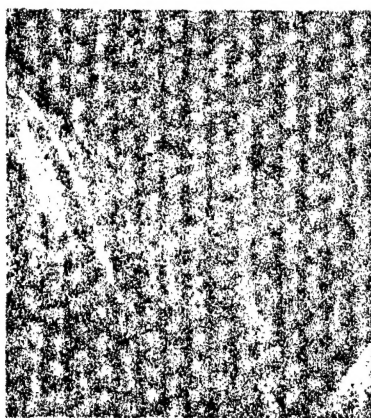


Figure 5. Photorecord of a "normal" detonation. The photograph was taken by a camera with increased resolving power. A mixture of  $2H_2 + O_2$ ,  $p_0 = 760$  mm of mercury;  $d = 15$  mm; increased in comparison with the characteristic along the z-axis:  $G = 3$ ; time scale  $t$  on the axis: 1 mm equals 0.2 microseconds.



Figure 6. The traced impression of a pulsating detonation. A mixture of  $2H_2 + O_2$ ;  $p_0 = 300$  mm of mercury;  $d = 16$  mm;  $G = 5$ ; the direction of the dilation of the detonation wave is from bottom to top; traces of the periodic bursts are indicated by the arrows.



Figure 7. Traced impressions of the detonation of a mixture of  $2H_2 + O_2$ . a, b - detonation;  $p_0 = 50$  mm of mercury;  $d = 11$  mm;  $G$ , for a, is 1.3;  $G$ , for b, is 2.25; c is pulsating detonation with  $n = z$ ;  $p_0 = 130$  mm of mercury;  $d = 11$  mm;  $G = 2.5$ .

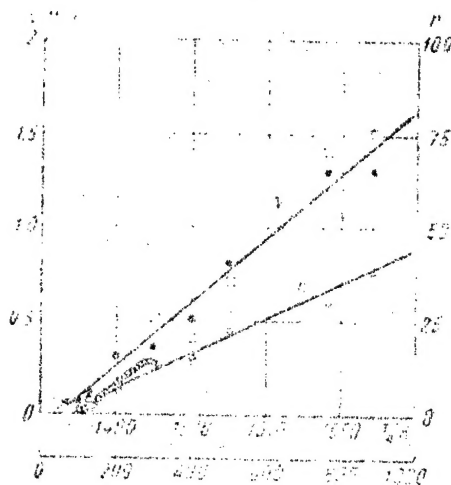
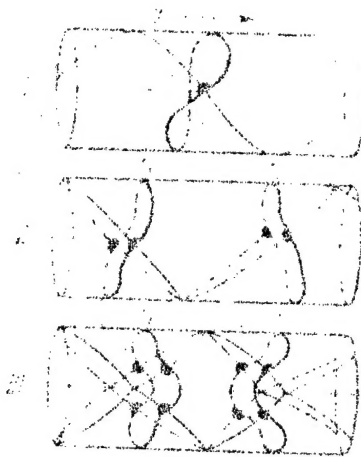
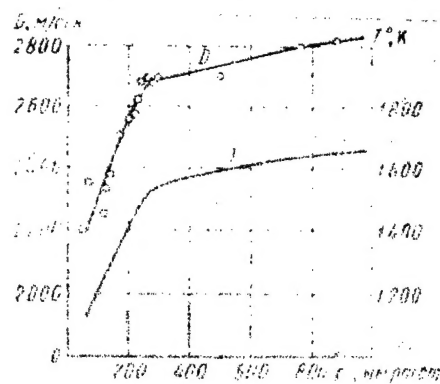


Figure 8. The relationships of the parameters of a detonation wave to the initial pressure of the reacting mixture (a mixture of  $2H_2 + O_2$ ;  $d = 16$  mm): a - detonation rate  $D$  and computation according to this rate of the average temperature  $T_A$  in the wave. b - leading front forms of detonation waves at times  $t_1$  and  $t_2$ ; I - spin [detonation]. II - pulsating [detonation] with  $n = 1$  number of pulsations in the tube's cross section; III - pulsating [detonation] with  $n = 2$ ; c - frequencies and number of pulsations  $n$ . The experimental points, included in the squares, have been obtained by the photo-scanning method, the others have been obtained by applying the trace method.